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Effects of Root Intrusion at the Burrell, Pennsylvania, Uranium Mill Tailings Disposal Site

W.J. Waugh
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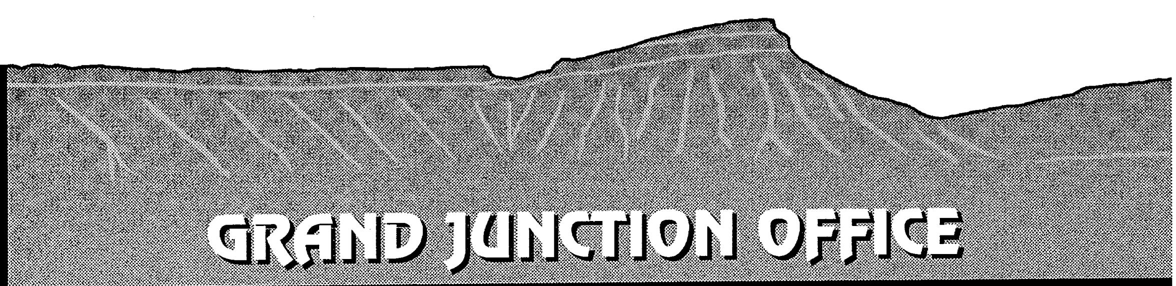
U.S. Department of Energy



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Prepared for
U.S. Department of Energy
Albuquerque Operations Office
Grand Junction Office
Grand Junction, Colorado

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Grand Junction, Colorado
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Executive Summary

The Burrell, Pennsylvania, disposal cell is a covered landfill constructed by the U.S. Department of Energy to isolate soil contaminated with uranium mill tailings. The abundance of plants growing on the Burrell disposal cell has increased annually since closure of the cell in 1987. DOE's original plan for postclosure maintenance included regular herbicide spraying to suppress plant growth for the 200-to-1,000-year life of the disposal cell. The purpose of this study was to determine current and possible long-term effects of plant root intrusion and ecological development on the performance of the disposal cell cover as the technical basis for a more tenable vegetation management program. This study focused on field measurements of factors that have the greatest influence on radon diffusion and water infiltration. Measurements at locations with and without plants on the Burrell disposal cell cover and at an analog site provided a reasonable range of current and possible long-term conditions.

The significant findings and recommendations of the study are

- Plant succession, root intrusion, and soil development in the radon barrier are inevitable. Research has shown that surface layers of rock reduce evaporation, increase soil water content, and create habitat for deep-rooted plants. Plant establishment and root intrusion can be controlled only with aggressive intervention of natural succession.
- The dominant plant currently rooting into the radon barrier is Japanese knotweed, an alien perennial with an exceptionally high rate of productivity. The leaf area index for Japanese knotweed at Burrell was greater than 0.5 in 1996. (Leaf area index is the ratio of canopy leaf area to soil surface area.) Without intervention, plant succession will probably lead to an open-canopy woodland within 30 to 50 years and a closed-canopy woodland with a leaf area index greater than 5.0 within 100 to 200 years.
- Plant root intrusion is not expected to cause radon flux rates to exceed the 20-picocuries-per-square-meter-per-second design standard during the 200-to-1,000-year design life of the disposal cell. Calculations made with the U.S. Nuclear Regulatory Commission's RADON computer code indicate that root intrusion presently has no significant influence on radon diffusion. Radon flux rates will increase over time as ^{230}Th decay raises ^{226}Ra activity in the disposal cell and as plant succession dries the soil and raises soil porosity. Much of the radon barrier's effectiveness derives from the fact that it consists of compacted material. The normal processes of soil formation will reverse that compaction, causing the radon barrier to gradually become less effective. However, unless unforeseen climatic changes dry the 90-centimeter radon barrier more than present ecological conditions allow, radon flux rates should remain below the design standard.
- The development of soil macropores in the radon barrier is the most detrimental effect of root intrusion. In situ measurements show that Japanese knotweed roots have already caused a hundredfold increase in saturated hydraulic conductivity (K_{sat}) beneath plants and an average tenfold increase overall. Measurements in an analog soil suggest that the K_{sat} value during the design life of the disposal cell may increase a thousandfold as root channels, earthworm holes, and soil structural development create preferred flow paths in the radon barrier.

A two-stage course of action is recommended:

1. Implement an interim herbicide spray program to control plant growth and root intrusion of the radon barrier. The program should target Japanese knotweed because this plant has had the greatest effect on the performance of the cover. Past herbicide applications have failed to control Japanese knotweed.

2. Conduct a screening-level risk assessment to evaluate the potential risks to human health and the environment associated with water infiltration of the cover and recharge through buried waste. The risk assessment methodology used by the Uranium Mill Tailings Remedial Action Ground Water Project should be implemented (DOE 1995a).

If the risk assessment indicates that increases in water infiltration at Burrell do not pose a significant risk to human health and the environment, maintenance of the cell need consist only of cutting mature trees to prevent pitting of the radon barrier as a consequence of tree fall. If the assessment indicates that increased water infiltration does pose a significant risk, corrective action to modify the cover design may be warranted.

1.0 Introduction

In 1978, Congress passed the Uranium Mill Tailings Radiation Control Act in response to public concern regarding potential human health and environmental effects associated with uranium mill tailings. The U.S. Department of Energy (DOE) is responsible for remedial action to bring surface- and ground-water contaminant levels at 24 inactive uranium mill sites into compliance with standards developed by the U.S. Environmental Protection Agency (EPA). DOE is accomplishing this through the Uranium Mill Tailings Remedial Action (UMTRA) Surface and Ground Water projects. The surface remedial action involves constructing an engineered soil cover to isolate contamination in a disposal cell. Surface contamination is either consolidated and covered in place or is moved into a landfill and covered. After remedial action is completed, DOE's Long-Term Surveillance and Maintenance (LTSM) Program monitors and maintains sites to ensure long-term protection of public health and the environment (DOE 1996).

Plant growth on the Burrell, Pennsylvania, uranium mill tailings disposal cell has raised concerns about the performance of its engineered cover. Plant abundance on the cover has increased annually since the disposal cell was closed in 1987. Some research suggests that plant root intrusion of engineered covers, like the one at Burrell, may increase radon flux, water infiltration, and biological transport of contaminants. For this reason, the Long-Term Surveillance Plan for Burrell recommends regular herbicide applications to suppress plant growth (DOE 1993). The UMTRA Project vegetation control strategy (DOE 1992) states that such "control measures will likely be required for the design life of the disposal cell." The design life criteria for UMTRA disposal cells is 200 to 1,000 years (EPA 1983).

Recent UMTRA guidance suggests that plant growth on rock covers is not necessarily detrimental and recommends "evaluations of all affected disposal cells" (DOE 1995b). For some types of cover designs and environmental settings, vegetation is beneficial and can enhance performance (Link et al. 1994). As custodian of licensed UMTRA disposal sites, the DOE LTSM Program recognizes the impracticality of committing to a 200-to-1,000-year herbicide spray program unless there are sound technical reasons to do so. This study evaluated possible consequences of root intrusion and ecological development on the Burrell engineered cover as the basis for a reasonable vegetation management strategy.

The study followed a stepwise decision process (Figure 1). Although ecological conditions and risks will vary among LTSM sites, Figure 1 is recommended as a model decision framework for evaluations of biointrusion at other sites. The decision path steps through four phases: justification, characterization, assessment, and implementation. Justification for vegetation management on disposal cells should be based on design and performance criteria or risk management needs. Our objectives were to evaluate (1) effects of root intrusion on cover design criteria for radon flux and water infiltration and (2) possible long-term ecological influences on cover performance. Because existing characterization data for Burrell were inadequate, our assessment focused on collection of field data for parameters that sensitivity analyses suggest have the greatest influence on radon flux and water infiltration (NRC 1989; Meyer et al. 1996).

The results warrant implementation of a strategy for control of plant growth until the human health and environmental risks of cover degradation can be assessed.

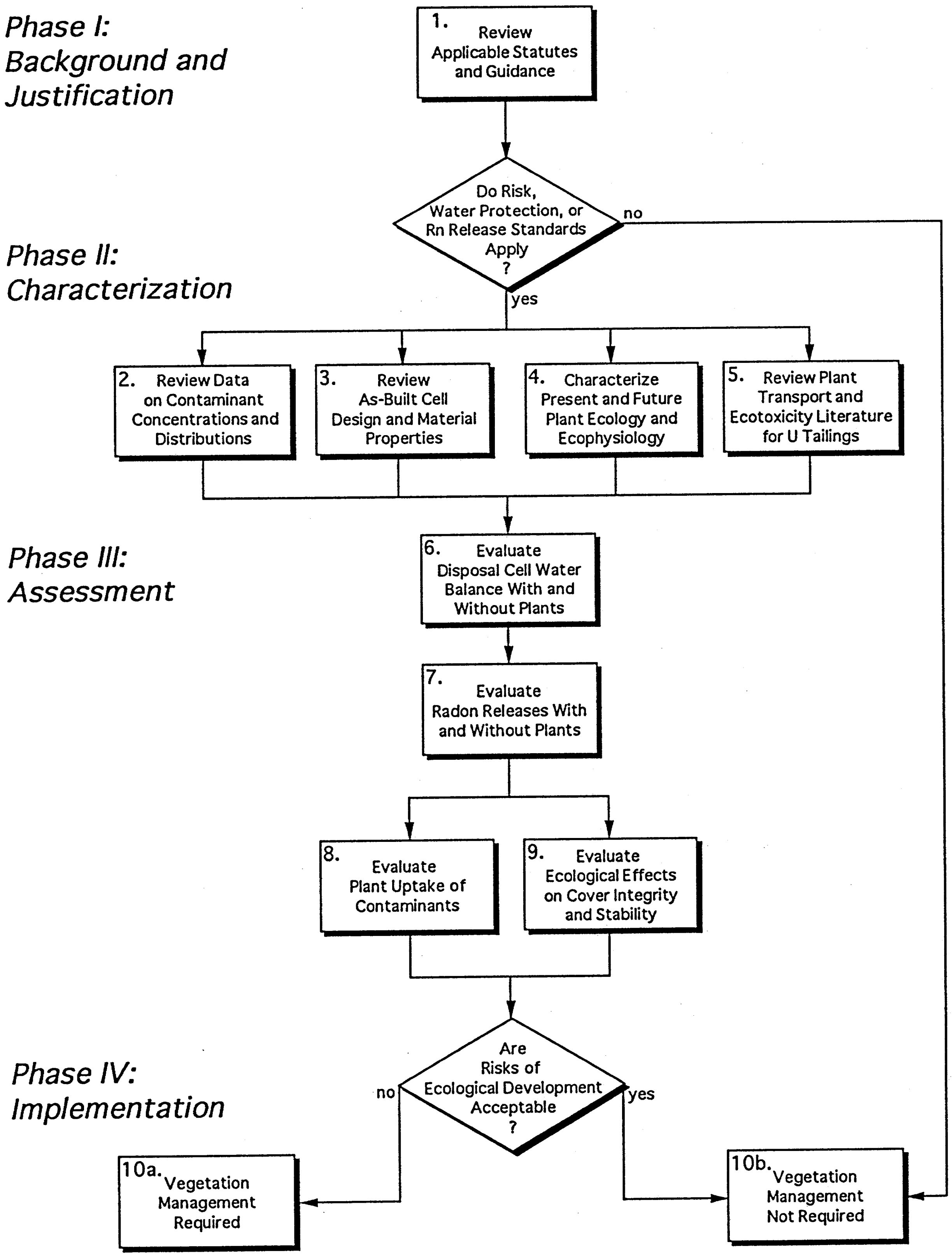

Figure 1. Framework for Evaluating Root Intrusion and Vegetation Management Needs on the Burrell Disposal Cell

2.0 Phase I: Background and Justification

2.1 Site Description and History

The Burrell site is a closed disposal cell located 1.5 kilometers east of the Borough of Blairsville, in the Burrell Township of Indiana County, approximately 72 kilometers east of downtown Pittsburgh, Pennsylvania. The site lies on the north side of a bend in the Conemaugh River approximately 16 kilometers upstream from the Conemaugh River Dam. Average daily temperatures range from –1.5 °C in January to 20 °C in July and August. The average annual precipitation is 112 centimeters (cm); the highest monthly precipitation occurs in June and July and the lowest occurs in December. The Burrell disposal cell was constructed on a large fill consisting of gravel, ash cinders, bricks, railroad ties, and other debris.

The Burrell disposal cell contains residual radioactive material (RRM). RRM at this site consists of soil contaminated with uranium mill tailings that were moved in 1956 and 1957 from the Vitro rare metals site at Canonsburg, Pennsylvania. RRM was originally stored in different locations around the site; some of it was used by the Pennsylvania Railroad as fill when its railroad tracks were rerouted. The Federal Government acquired a 29-hectare tract enclosing the contaminated property in 1986 through condemnation proceedings. Remedial action involved the excavation and consolidation of contaminated soils and mill tailings in a 2.5-hectare disposal cell. Construction of the Burrell disposal cell was completed in July 1987.

2.2 Applicable Statutes and Guidance

Long-term vegetation management decisions at Burrell should be based on regulatory standards and UMTRA Project guidance for the protection of human health and the environment; maintenance activities should satisfy regulatory compliance needs. The standards that could reasonably be influenced by root intrusion at the Burrell disposal cell pertain to radon attenuation, water resource protection, biological transport pathways, and design life of the cover. These standards and guidance reflect congressional desire for long-term solutions that incorporate passive, low-maintenance designs (DOE 1989).

2.2.1 Radon Attenuation

The design standard for radon [40 *Code of Federal Regulations* (CFR) 192.02(b)] states that the remedial action should provide reasonable assurance that releases of ^{222}Rn from RRM to the atmosphere will not (1) exceed an average surface flux rate of 20 picocuries per square meter per second ($pCi \cdot m^{-2} \cdot s^{-1}$) or (2) increase the average concentration of ^{222}Rn in the air at or above any location outside the disposal site by more than 0.5 picocurie per liter (pCi/L). The regulation allows averaging over periods of 1 year or longer. We assumed that significant changes in radon diffusion parameters attributable to root intrusion would warrant vegetation management.

2.2.2 Water Resources Protection

In 1995, EPA published 60 *Federal Register* (FR) 2854, the Final Rule for control of RRM from inactive uranium processing sites, which requires that remedial action be conducted to ensure that amounts of RRM and associated hazardous constituents in ground water meet certain concentration standards. Compliance with ground-water standards depends on an engineered cover that limits infiltration of meteoric water into buried RRM (DOE 1989). This is achieved by maintaining unsaturated conditions in the cover, by including a highly permeable bedding or drainage layer in the cover, and/or by including a compacted, low-permeability soil layer in the cover. We assumed that significant increases in water movement through the Burrell cover, potentially releasing RRM and associated hazardous constituents to ground water, would warrant vegetation management.

2.2.3 Biological Transport Pathways

Plant uptake of RRM and associated metals is a potential release pathway. We assumed that if the potential for plant uptake of contaminants exists at Burrell, then root growth through the cover into the RRM would warrant vegetation management.

2.2.4 Design Life

EPA established a standard for the design life of remediated sites of 1,000 years whenever reasonably achievable; in any case, a minimum performance period of 200 years must be achieved (EPA 1983). We assumed that the present plant community at Burrell is an early successional phase and that as the plant community changes the effects of root intrusion will likely surpass what has occurred thus far. Therefore, this study was designed to project possible ranges of ecological change that could occur tens-to-hundreds of years in the future.

2.3 Review of Plant Ecology and Long-Term Performance Issues

Growth of vegetation on the Burrell cover should have been anticipated. Surface layers of rock reduce evaporation (Groenevelt et al. 1989), increase soil water storage (Kemper et al. 1994), and, consequently, create habitat for deep-rooted plants. Vegetation management decisions should rely on an understanding of the potential roles plants play, beneficial as well as detrimental, on the performance and longevity of the cover. The overall role of plant ecology in the process of designing and evaluating engineered covers is addressed by Hakonson et al. (1992), Link et al. (1994), Suter et al. (1993), and Waugh et al. (1994). A brief review follows.

2.3.1 Beneficial Effects

Protection of water resources from contaminants in uranium mill tailings has become a priority for remedial action. Accordingly, a central question with respect to long-term maintenance of vegetation at Burrell is whether plants on the cover will increase or decrease the likelihood of contaminant discharge from the disposal cell. This issue can be argued both ways. Decaying plant roots may create conduits through which water and gases readily pass, thus potentially increasing water infiltration and contaminant discharge. Conversely, extraction of soil water from the cover by plants (transpiration) may significantly decrease infiltration. Many disposal cell cover designs rely on a combination of plant transpiration and soil evaporation (evapotranspiration) to maintain infiltration at acceptable levels (Waugh et al. 1991; Gee and Wing 1994; Nyhan et al. 1990; Anderson et al. 1993). Even in humid climates, such as in western Pennsylvania where precipitation exceeds potential evapotranspiration, water extraction by plants may account for more than half of the soil water loss from disposal cell covers (Melchior et al. 1994).

Vegetation may also improve slope stability. Vegetation helps disperse raindrop energy, slow runoff flow velocity, filter sediment from runoff, bind soil particles, and deplete soil moisture, thereby delaying the onset of saturation and runoff (Wischmeier and Smith 1978). Woody vegetation has been shown to improve the stability of riprap-armored slopes (Shields 1991). However, the complexity of vegetation and rock-slope interactions has hampered efforts to quantify their role in stability analyses (Greenway 1987; Morgan and Rickson 1995).

2.3.2 Detrimental Effects

Although plants may improve the performance of the Burrell cover with respect to soil water extraction and slope stability, deep-rooted plants may counteract these benefits. Plants can root through soil covers into underlying waste material, actively translocating and disseminating contaminants in aboveground tissues. Plants rooted in uranium-bearing materials may contain elevated levels of uranium, molybdenum, selenium, radium-226, thorium-230, and polonium-210 (Clulow et al. 1991; Dreesen and Williams 1982; Driver 1994; Hosner et al. 1992; Lapham et al. 1989; Markose 1993). Plants rooted in uranium mill tailings may also increase releases of ^{222}Rn to the atmosphere. Radon can be transported into the atmosphere as plants extract water from tailings (Lewis and MacDonell 1986, 1990; Morris and Fraley 1989). Roots may also alter waste chemistry, potentially mobilizing contaminants (Cataldo et al. 1987; Driver 1994).

Root intrusion may physically degrade the performance of the Burrell cover. During the past several years, evidence has mounted that covers with compacted soil layers are vulnerable to desiccation and cracking from wet-dry cycles, freeze-thaw cycles, and biointrusion (Melchoir et al. 1994; Kim and Daniel 1992; Reynolds 1990; Hakonson 1986). Macropores left by decomposing plant roots can act as channels for water and gases to rapidly bypass the soil mass in compacted soil layers (Hillel 1980; Passioura 1991). The greatest effect of plant roots on radon may be by alteration of the diffusivity and permeability of the compacted soil (Schery 1989) rather than by active transport. Plant roots also tend to concentrate in and extract water from compacted clay layers, causing desiccation and cracking (Reynolds 1990). This can occur even when overlying soils are nearly saturated (Hakonson 1986), suggesting that the rate of water extraction by plants may exceed the rehydration rate of the compacted clay. In addition, roots may clog the lateral drainage layer (DOE 1992), potentially increasing rates of infiltration through the underlying compacted soil.

Plant community development on the cover may create habitat for animals. Burrowing and tunneling animals can mobilize contaminants by vertical displacement of waste or by altering erosion, water balance, and gas release processes (Hakonson et al. 1992; Suter et al. 1993).

Vertical displacement results as animals excavate burrows and ingest or transport contaminants on skin and fur (Hakonson et al. 1982; McKenzie et al. 1982). Once in the surface environment, contaminants may then be transferred through higher trophic levels and carried off site (O'Farrell and Gilbert 1975; Arthur and Markham 1983). Loose soil cast to the surface by burrowing animals is vulnerable to wind and water erosion (Winsor and Whicker 1980; Cadwell et al. 1989). Burrowing and tunneling influences soil water balance and radon releases by decreasing runoff, increasing rates of water infiltration and gas diffusion, and, in some cases, increasing evaporation through natural drafts (Cadwell et al. 1989; Sejkora 1989; Landeen 1994).

2.3.3 Ecological Change and Natural Analogs

Changes in the plant community are inevitable. Ecological change on the cover will be driven by many interacting factors that not only vary over time and space but also exhibit concomitant and synergistic effects. Plant communities change in response to several interacting factors: propagule accessibility, climatic variability, change in soil characteristics, disturbances (such as fire and disease), and species interactions (such as herbivory, competition, or fluctuations in soil microbe populations). Plant community dynamics are manifested by shifts in vegetation abundance, species composition, and diversity and may be accompanied by changes in rates of nutrient cycling, energy exchange, and transpiration. Therefore, as the plant community changes, the performance of the cover may respond in ways that cannot be predicted by short-term field tests and numerical models. For example, microtopographical patterns may emerge that foster greater heterogeneity in the plant community and the soil water balance. At Burrell, future blowdown of mature trees on the cover could locally reduce the effective thickness of the cover and create depressions for water accumulation (Suter et al. 1993).

Changes in the plant community will be accompanied by pedogenic (soil development) processes. Pedogenic processes may alter the physical and hydraulic properties of engineered soil layers in the cover. Pedogenesis includes processes such as soil structural development (dispersion or flocculation of fines and development of macropores), secondary mineralization and illuviation of materials causing the formation of distinct layers or horizons, and pedoturbation (natural soil mixing). Although rates and magnitudes vary, pedogenesis takes place to some degree in all soils (Boul et al. 1980). Rates of soil development are greatest in engineered soils in response to plant succession.

The evolution and architecture of macropores associated with root growth, animal holes, and soil structural development are highly relevant to the long-term performance of the Burrell cover. Overall, soil structural development creates preferential flow paths under saturated conditions (Collis-George 1991), causing fine-textured soil layers to behave more like a coarse, gravely soil with respect to water movement. Eluviation and illuviation (similar to emigration and immigration) of fine particles, colloids, soluble salts, and oxides in an engineered cover may create secondary layers or horizons with diverging physical and hydraulic characteristics (Boul et al. 1980). Accumulation of these materials in the macropores of sand and gravel layers in engineered covers could reduce the permeability of lateral drainage layers, increase the rate of downward redistribution of water through capillary barriers, and reduce the water storage capacity of overlying soil layers.

No unequivocal prediction can be made about the influences of long-term plant succession and soil development on the performance of the Burrell cover, but natural analogs can help. Natural analogs provide clues from present and past environments about possible long-term bounding conditions in engineered covers (Waugh et al. 1994). Analog studies involve the use of logical analogy to investigate natural materials, conditions, or processes that are similar to those known or predicted to occur in some component of an engineered cover system. As such, analogs can be considered uncontrolled, long-term experiments. Evidence from natural analogs is the only means to project emergent properties in the evolution of engineered covers that cannot be captured with short-term monitoring of the cover or with numerical models. Ecological factors expected to have the greatest influence on the long-term performance of the cover can be evaluated by comparing soils and vegetation on the disposal cell with conditions at analog sites. Natural analogs may also have a role in communicating the results of a performance assessment to the public. Evidence from natural systems may help demonstrate that numerical predictions have real-world complements.

3.0 Phase II: Characterization

Phase II of the study compiled existing site characterization data needed to evaluate root intrusion effects on the cover.

3.1 Contaminant Concentrations and Distributions

Evaluations of root intrusion effects on water infiltration, radon diffusion, plant uptake, and eventually on the human health and ecological risks associated with release pathways require data on the chemical species, concentrations, and distributions of contaminants in the Burrell disposal cell. Data on concentrations and distributions of radiological (^{226}Ra and ^{230}Th) and other contaminants are presented in the Burrell completion report (MKE 1994). The estimated total ^{226}Ra activity in the 54,000 cubic yards of contaminated material placed in the cell is about 4 curies. The completion report did not contain an estimate of the ^{230}Th inventory. Table 1 presents a summary of as-built ^{226}Ra and ^{230}Th data from a grid of 24 boreholes sampled in November 1986 after RRM was placed in the cell but before the cover was constructed.

Table 1. Summary Statistics for ^{226}Ra and ^{230}Th Concentrations in the Burrell Disposal Cell

Depth	^{226}Ra (pCi/g)[a]					^{230}Th (pCi/g)				
(cm)	Mean	SE (mean)[b]	Min.	Max.	*n*[c]	Mean	SE (mean)	Min.	Max.	*n*
0 – 60	39.5	8.0	5.5	85.0	11	416.0	154.6	55.0	1910.0	11
60 – 120	26.5	5.3	8.0	83.0	12	204.1	32.1	77.0	410.0	12
120 – 300	79.8	18.8	28.0	280.0	13	878.5	171.9	350.0	2520.0	13
All	49.6	8.2	5.5	280.0	36	512.4	90.7	55.0	2520.0	36

[a]pCi/g = picocuries per gram.
[b]Standard error of the mean.
[c]Number of samples.

Lateral and vertical heterogeneities of ^{226}Ra and ^{230}Th concentrations were high. Overall, concentrations were lower beneath the top slope and higher beneath the side slopes of the cell. Radon emanation fraction data, required for modeling radon flux, were also compiled from the completion report (Table 2).

Chemical analyses of soil extracts from the Burrell site were performed in 1984. These analyses included pesticides (Methoxychlor, 2,4-D, and 2,4,5-T), metals (arsenic, barium, cadmium, lead, mercury, selenium, and silver), sulfide, and cyanide. According to Morrison-Knudsen Engineers, Inc. (MKE 1988), no results for pesticides exceeded the EPA maximum allowable toxicity concentrations given in 40 CFR 261.24. Except for one cadmium value, MKE (1988) also states that no metal concentrations exceeded the maximum EPA toxicity limits for metals in 40 CFR 261.24. Therefore, for the purposes of this study, we assumed that no nonradiological hazards exist at the site.

Table 2. Radon Emanation Fraction Data for the Burrell Disposal Cell

Depth (cm)	Mean	SE (mean)[a]	Min.	Max.	*n*[b]
0 – 60	0.14	0.011	0.04	0.23	22
60 – 120	0.13	0.014	0.01	0.27	23
120 – 180	0.15	0.013	0.00	0.23	23
180 – 240	0.17	0.015	0.00	0.31	24
240 – 300	0.16	0.016	0.02	0.29	22
All	0.15	0.006	0.00	0.31	114

[a]Standard error of the mean.
[b]Number of samples.

3.2 Cover Design and Material Properties

As-built information on the soil, sand, and rock layer thicknesses; material properties (e.g., liquid limit, plasticity, texture, bulk density); and hydraulic properties (e.g., saturated conductivity and water retention characteristics) were compiled for use in radon flux and water infiltration evaluations.

From the RRM layer upward, the Burrell cover consists of a 90-cm-thick radon barrier or compacted soil layer (CSL), a 30-cm-thick sand and gravel drainage layer, and a 30-cm-thick rock layer (Figure 2). These three layers were designed to function together to meet the regulatory standards for radon releases and erosion for 200 to 1,000 years. The target hydraulic conductivity for the CSL was 1×10^{-7} centimeter per second (cm/s). A CSL thickness adequate to meet the radon flux standard was calculated with the U.S. Nuclear Regulatory Commission (NRC) RADON computer modeling code (NRC 1989).

The sand and gravel drainage or filter layer also serves as a bedding layer for the rock armor. The rock armor is sized to prevent erosion of underlying layers given a probable maximum precipitation (PMP) event, the most severe combination of meteorological and hydrological conditions possible at a site (DOE 1989).

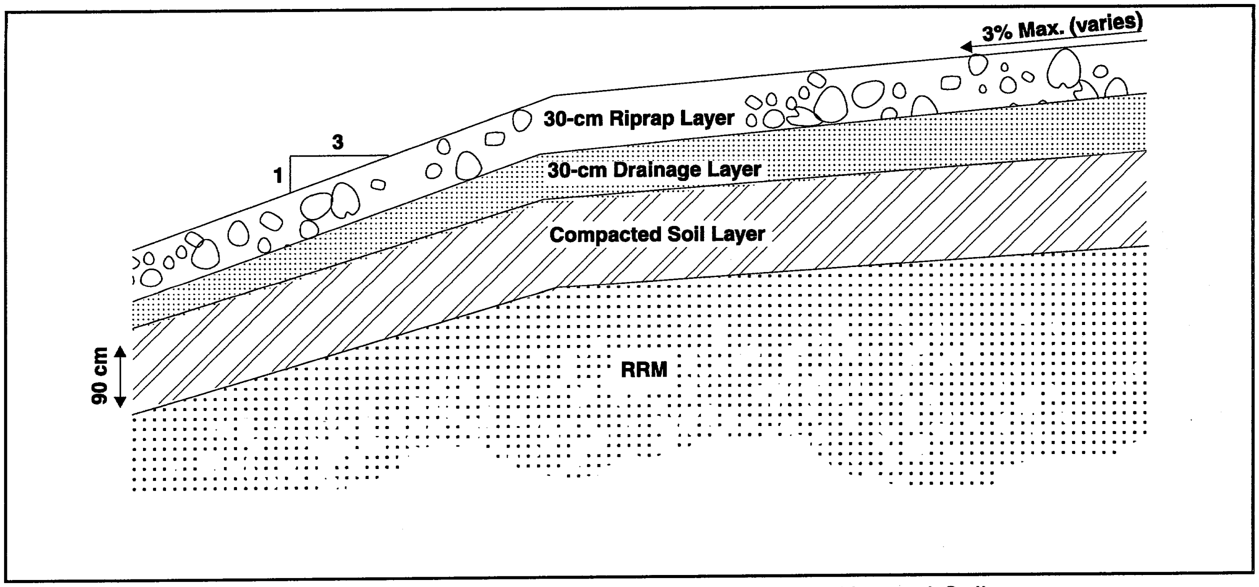

Figure 2. Surface Cover Design for the Burrell Disposal Cell

Material property data for the CSL (Table 3) were compiled from the completion report for Burrell (MKE 1994). Actual compaction of the radon barrier during construction averaged 96.6 percent of the maximum dry density. Actual average, maximum, and minimum gravimetric moisture content of the radon barrier during construction were 17.7 percent, 21.7 percent, and 14.7 percent, respectively. The bedding and rock riprap materials are a greenish gray, calcareous, crossbedded sandstone. Grain-size curves for these materials are available in the completion report (MKE 1994).

Table 3. Summary of Engineering Test Results for Compacted Soil Layer

								Proctor Compaction	
Soil Type[a]	Specific Gravity	Liquid Limit (%)	Plasticity Index (%)	% Passing 200 Sieve	Silt (%)	Clay (%)	Moisture Content (%)	Optimum % Moisture	Max. Dry Density
CL[b]	2.66	35.8	16.0	62	38	24	16.7	16.9	1.73 g/cm^3

[a]Unified Soil Classification System.
[b]Silty clay with some coarse fragments.

3.3 Burrell Cover Vegetation Management

Five reports published by the UMTRA Project document the establishment and rooting patterns of plants on the Burrell disposal cell since its completion in 1987. Table 4 presents a comprehensive list of plant species observed on the Burrell disposal cell between 1990 and 1996. Studies completed in 1988 and 1990 documented the occurrence of vegetation on the disposal cell and the growth of plant roots into the compacted soil layer of the cover (DOE 1988, 1990). A more detailed assessment conducted in 1991 produced a comprehensive list of plant species and documented the density, relative abundance, dimensions, and rooting patterns of the species of

Table 4. Plant Species Observed on the Burrell, Pennsylvania, Disposal Cell Between 1990 and 1996

Common Name	Scientific Name
Big-toothed aspen	*Populus grandidentata*
Black cherry	*Prunus serotina*
Black locust	*Robinia pseudo-acacia*
Black raspberry	*Rubus occidentalis*
Blackberry	*Rubus allegheniensis*
Bouncing bet	*Saponaria officinalis*
Boxelder	*Acer negundo*
Bull thistle	*Cirsium vulgare*
Canada thistle	*Cirsium arvense*
Catnip	*Nepeta cataria*
Common catalpa	*Catalpa bignonioides*
Common plantain	*Plantago major*
Common St. Johnswort	*Hypericum perforatum*
Crown vetch	*Coronilla varia*
Curled dock	*Rumex cripus*
Dandelion	*Taraxacum officinale*
Dogbane	*Apocynum spp.*
Giant mullein	*Verbascum thapsus*
Goldenrod	*Solidago spp.*
Hop clover	*Trifolium agrarium*
Japanese knotweed	*Polygonum cuspidatum*
Jewelweed	*Impatiens spp.*
Moth mullein	*Verbascum blattaria*
Mother wort	*Leonurus cardiaca*
Multiflora rose	*Rosa multiflora*
Ox-eye	*Heliopsis helianthoides*
Purple clematis	*Clematis verticillaris*
Purple loosestrife	*Lythrum salicaria*
Quaking aspen	*Populus tremuloides*
Queen Anne's lace	*Daucus carota*
Red raspberry	*Rubus idaeus*
Red swamp current	*Ribes triste*
Spotted joe-pye weed	*Eupatorium maculatum*
Spotted knapweed	*Centaurea maculosa*
Staghorn sumac	*Rhus typhina*
Sugar maple	*Acer saccharum*
Sycamore	*Platanus occidentalis*
Teasel	*Dipsacus sylvestris*
Tree-of-heaven	*Ailanthus altissima*
Tuliptree	*Liriodendron tulipifera*
Virginia creeper	*Pathenocissus quinquefolia*
White ash	*Fraxinus americana*
White snakeroot	*Eupatorium rugosum*
White sweet clover	*Melilotus alba*
Wild grape	*Vitis sp.*
Willow sp.	*Salix sp.*
Yellow sweet clover	*Melilotus officinalis*
Yellow birch	*Betula lutea*

greatest concern (DOE 1992). Four tree species (sycamore, box elder, black locust, and tree-of-heaven) had rooted as deep as 33 cm into the compacted soil layer. An exotic perennial forb, Japanese knotweed, had rooted 46 cm into the compacted soil layer. The 1992 report also identified possible detrimental effects of plant growth on the performance of the cover and recommended an herbicide spray program to "eliminate Japanese knotweed and tree species from the cover." All Japanese knotweed and woody plants on the disposal cell were sprayed with herbicides in August 1992, excluding a 0.5-hectare study plot that was established in June 1992 to monitor the effects of plant encroachment.

In 1993, herbaceous species and some trees as tall as 1 meter were observed in areas on the disposal cell that had been treated with herbicides the previous year (DOE 1993), indicating that annual herbicide applications may be required if the vegetation management goal is to eliminate trees from the cover. In 1994, robust growth of herbaceous and woody vegetation was observed over nearly all the disposal cell (DOE 1994). The number, density, cover, and size of plant species were visibly greater between 1993 and 1994. By 1996, plants were as abundant in areas sprayed during 1992 as in the 0.5-hectare plot that has not been sprayed since closure of the cell in 1987.

4.0 Phase III: Assessment

This study encompassed both current conditions and possible long-term effects of root intrusion on radon flux and water infiltration. We evaluated current influences of plants by comparing locations on the Burrell cover with and without plants. We inferred the potential long-term condition of the cover, if ecological development continues unimpeded, using data from a natural analog site (see Section 2.3.3).

4.1 Natural Analog Site Selection

Three criteria helped guide our search for an appropriate natural analog of possible future ecological conditions on the Burrell cover: (1) same soil type as the radon barrier, (2) a soil depth equal to or greater than the radon barrier, and (3) a chronosequence of plant community development with the oldest sere (successional stage) at least 50 years old.

The following sequence of activities led to the selection of the Hannastown Historical Park in Westmoreland County, Pennsylvania, as a natural analog site:

1. ***Determine the source of the radon barrier material.***

   The completion report (MKE 1994) indicated that the radon barrier material was overburden soil from the Blue Jay Coal Mine located approximately 4 kilometers southwest of the Burrell site in Westmoreland County.

2. ***Determine the soil series.***

   A copy of the U.S. Department of Agriculture (USDA) Soil Survey for Westmoreland County was obtained from the Natural Resource Conservation Service office in Greensburg, Pennsylvania (Taylor et al. 1992). That document contains maps of soil series delineated on 1967 aerial photographs. The following soil series were depicted within the property boundaries of the Blue Jay Coal Mine, which has since been reclaimed:

   Gilpen channery silt loam
   GcB2 – 5 to 12 percent slopes

   Westmoreland silt loam
   WmB2 – 5 to 12 percent slopes
   WmC2 – 12 to 20 percent slopes

   Gurnsey silt loam
   GsB2 – 3 to 8 percent slope
   GsC2 – 8 to 15 percent slope

   The Burrell radon barrier was constructed in 1987. We used a sequence of aerial photographs obtained from the Westmoreland County Conservation District office to determine the location of open or active pits at the Blue Jay Coal Mine between 1985 and 1987 and the respective locations of soil mapping units for the pits. Pits were active between 1985 and 1987 in both the Gurnsey silt loam and Westmoreland silt loam series.

3. ***Locate candidate analog sites.***

   Land parcels with mature vegetation within the Westmoreland silt loam and Gurnsey silt loam series were located using the USDA soil survey maps. Surface features such as woodlands, cultivated land, buildings, and roads were readily discernable on the photographs. Several parcels were chosen as candidate analog sites. We visited the Westmoreland County Assessor's Office in Greensburg to determine land ownership.

4. ***Select an analog site.***

   Hannastown Historical Park, an archaeological and historical site owned and managed by the Westmoreland County Historical Society, was selected as an ecological analog of the Burrell cover on the basis of the following attributes:

   Soils. Soils of the Hannastown Historical Park are primarily Westmoreland silt loam and Gurnsey silt loam with thick silty clay and silty clay loam subsoils consistent with the Blue Jay Coal Mine overburden. An inspection of open archaeological and construction excavations confirmed the soil survey map delineations for the Hannastown site.

   Vegetation. A chronosequence of old-field plant succession at the site includes cultivated land, pasture, and second-growth woodland. According to a long-time resident and employee of the Westmoreland County Historical Society, some woodland areas in the park have not been cut since the 19th century.

   Accessibility. The Westmoreland County Historical Society approved our request to characterize and sample soils and vegetation within the park boundaries. Most of the park proper is accessible by foot a short distance from roads.

   A 0.5-hectare rectangular area near the northeast corner of Hannastown Historical Park was chosen for study. The second-growth, closed-canopy woodland consists primarily of sugar maple with scattered beech and yellow birch and virtually no understory vegetation. The northeast-facing stand has a slope of approximately 5 percent. The soil series, Westmoreland silt loam, formed in residuum derived from interbedded gray calcareous shale, sandstone, and limestone. The soil profile at the study site consisted of a 15- to 20-cm brown, silt loam plow layer over a 80+ cm yellowish-brown silty clay loam subsoil.

4.2 Soil Physical and Hydraulic Properties: Methods and Results

A field measurement and sampling program was developed to acquire data that best capture near-term and possible long-term influences of ecological development on the performance of the cover. These data were used for analyses of radon flux and water infiltration (Sections 4.3 and 4.4, respectively). Three conditions were compared: (1) Burrell cover without plant roots (as-built), (2) Burrell cover with plant roots, and (3) the Hannastown analog of a possible future Burrell cover ecology.

4.2.1 Soil Water Content, Texture, Bulk Density, and Porosity

Soil samples were retrieved from the Burrell cover and from analog soil profiles at Hannastown to determine seasonal soil water content, texture (particle size distribution), bulk density (compaction), and porosity. Soil pits were excavated in the Burrell cover with hand tools in locations both with and without vegetation ($n = 5$). At locations with vegetation, pits were excavated through the root crowns of mature Japanese knotweed. The surface layer of rock was moved to expose the gravel bedding layer. For water content and textural analyses, loose bedding layer material was sampled at the contact with the CSL; a bucket auger was used to retrieve CSL samples. We sampled early in the growing season and again in mid-summer to capture seasonal variation in soil water content. Plow-layer and subsoil samples from random soil profiles ($n = 5$) at the Hannastown site were also retrieved with a bucket auger. Bulk density samples of the Burrell CSL and the Hannastown subsoil were retrieved with a double cylinder, hammer-driven core sampler. Table 5 presents the methods used for analyses of gravimetric water content, soil particle size, bulk density, and porosity; Tables 6 and 7 present the results of these analyses.

Table 5. Summary of Laboratory Methods for Soil Analyses

Soil Property and Method	Reference
Gravimetric Water Content	Klute (1986), Chapter 21, pp. 493–544
Particle Size Distribution	
Sieve	American Standard and Testing (ASTM) D422–63 (90)
Hydrometer	ASTM D422–63 (90)
Dry-Weight Bulk Density	Klute (1986), Chapter 13, pp. 363–367
Soil Porosity	Klute (1986), Chapter 18, pp. 444–445
Saturated Hydraulic Conductivity	
Falling Head Method	Klute (1986), Chapter 28, pp. 700–703
Moisture Retention Characteristics	
Hanging Column	Klute (1986), Chapter 26, pp. 637–639
Pressure Plate	ASTM D2325–68 (81)
Thermocouple Psychrometer	Klute (1986), Chapter 24, pp. 597–618 Deagon Devices, Inc., Pullman, Washington

Table 6. Particle Size and Bulk Density of the Burrell CSL and Hannastown Analog Subsoil

Site	Particle Size[a]		Bulk Density (g/cm³)		
	% Clay	% Sand	Mean	SE (mean)[b]	*n*
Burrell Cover					
With Plants	27	39	1.76	0.02	5
Without Plants	—	—	1.77	0.02	5
Hannastown Analog Site	29	17	1.48	0.02	5

[a]USDA Soil Classification System.
[b]Standard error of the mean.

Table 7. Gravimetric and Volumetric Soil Water Content in the Burrell Cover and in Analog Soil Profiles at Hannastown Historical Park

Site	Date	Material Type	Depth (cm)	Soil Water Content (% dry-weight)		Soil Water Content (% Volume)[a]		
				Mean	SE (mean)[b]	Mean[c]	SE (mean)	*n*
Burrell Cover Without Plants	May 10, 1995	Drainage Layer	15	4.3	0.6			5
		Drainage Layer	30–45	4.3	0.3			5
		Radon Barrier	15	20.3	1.0	35.9(a)	1.0	5
		Radon Barrier	45–60	19.3	0.7	34.2(b)	0.7	5
Burrell Cover Without Plants	July 28, 1995	Drainage Layer	30–45	4.7	0.2			5
		Radon Barrier	15	18.2	0.9	32.2(a)	0.9	5
		Radon Barrier	30–60	19.2	0.5	34.1(a)	0.5	5
Burrell Cover With Plants	July 28, 1995	Drainage Layer	30–45	4.8	0.2			5
		Radon Barrier	15	19.1	0.7	33.6(a)	0.7	5
		Radon Barrier	30	18.8	0.3	33.2(a)	0.3	5
		Radon Barrier	50–60	18.3	0.2	32.2(a)	0.2	4
Hannastown Historical Park Analog Site	July 28, 1995	A-Horizon	15	17.8	0.9			5
		B-Horizon	60	17.0	0.6	25.1(b)	0.6	5
		B-Horizon	110	16.5	0.7	24.4(b)	0.7	5

[a]Calculated using bulk density values from Table 6.
[b]Standard error of the mean.
[c]Means marked with the same letter are not significantly different ($\alpha = 0.05$).

4.2.2 Laboratory Soil Hydraulic Properties

Soil hydraulic properties of the Burrell CSL and the Hannastown subsoil were compared as a measure of the value of Hannastown as an analog site. These data were also needed for radon flux and water infiltration analyses (Sections 4.3 and 4.4, respectively). Saturated hydraulic conductivity and water retention characteristics were determined using standard laboratory methods (Table 5). For these tests, samples were recompacted at bulk densities consistent with field values (Table 6). The RETC code (van Genuchten et al. 1991) was used to quantify unsaturated soil-water retention characteristics and curve fitting. Table 8 and Figures 3 through 6 present summaries of results of soil moisture characteristics.

Table 8. Laboratory Results of Saturated Hydraulic Conductivity (K_{sat})*, Initial Test Conditions, and Water Retention Characteristics for Recompacted Burrell CSL and Hannastown Analog Subsoil*

	Initial Test Conditions					Water Retention Characteristics				
Sample No.	θ_g [a]	θ_v [b]	ρ_b [c]	S_t [d]	K_{sat} (cm/s)	θ_s [e]	θ_r [f]	n [g]	α [g]	r^2 [h]
Burrell CSL 1	19.0	33.9	1.78	32.7	2.6×10^{-8}	36.4	0.10	1.524	0.0001	0.963
Burrell CSL 2	18.5	33.2	1.79	32.5	3.3×10^{-8}	36.7	0.06	1.163	0.0014	0.966
Hannastown 1	16.2	24.1	1.48	44.0	1.4×10^{-7}	43.1	0.02	1.312	0.0022	0.993
Hannastown 2	16.0	23.8	1.49	44.0	5.1×10^{-7}	40.8	0.08	1.416	0.0008	0.999

[a]Gravimetric percent water content.
[b]Volumetric percent water content.
[c]Dry-weight bulk density (g/cm^3).
[d]Total porosity in centimeters per second calculated as $1 - \rho_b/\rho_p$ with an assumed particle density, ρ_p, of 2.65 g/cm^3.
[e]Saturated water content as % volumetric; the maximum volumetric water content of the soil.
[f]Residual water content; the maximum amount of water in a soil that will not contribute to liquid flow.
[g]The symbols n and α are empirical curve-fitting constants that affect the shape of the water retention curve using the equation of van Genuchten (1980).
[h]The coefficient of determination is a measure of how well the van Genuchten curve fits the observed data.

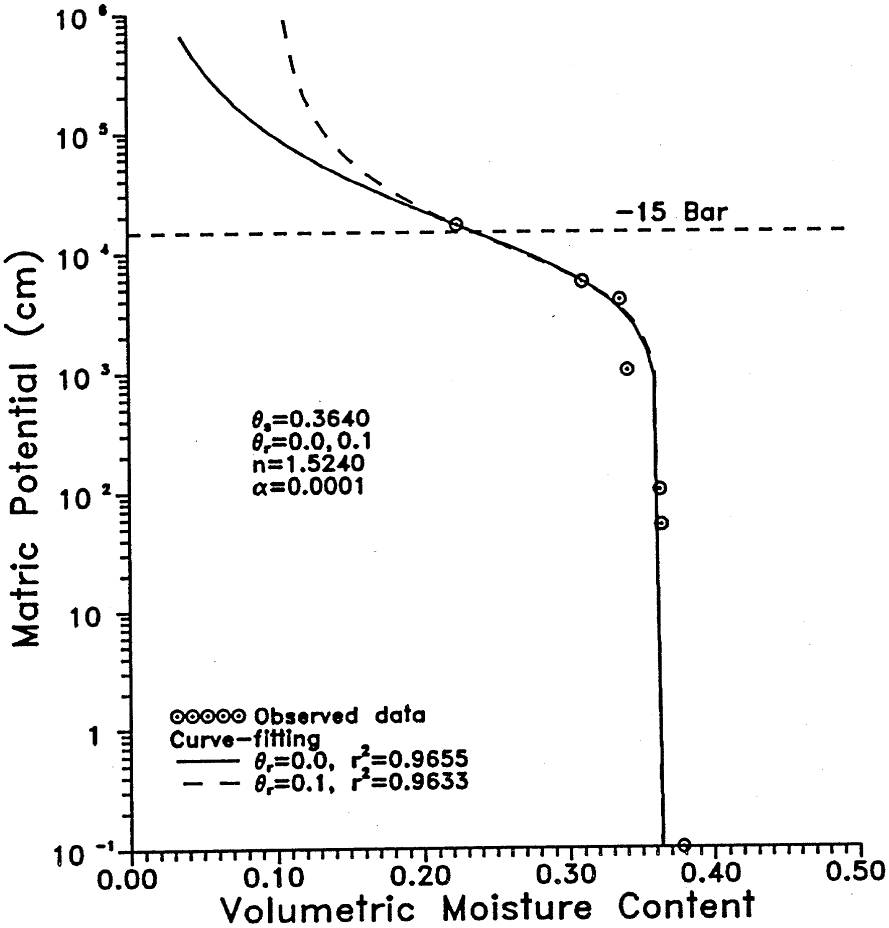

Figure 3. Soil Moisture Characteristics for Burrell CSL Sample 1

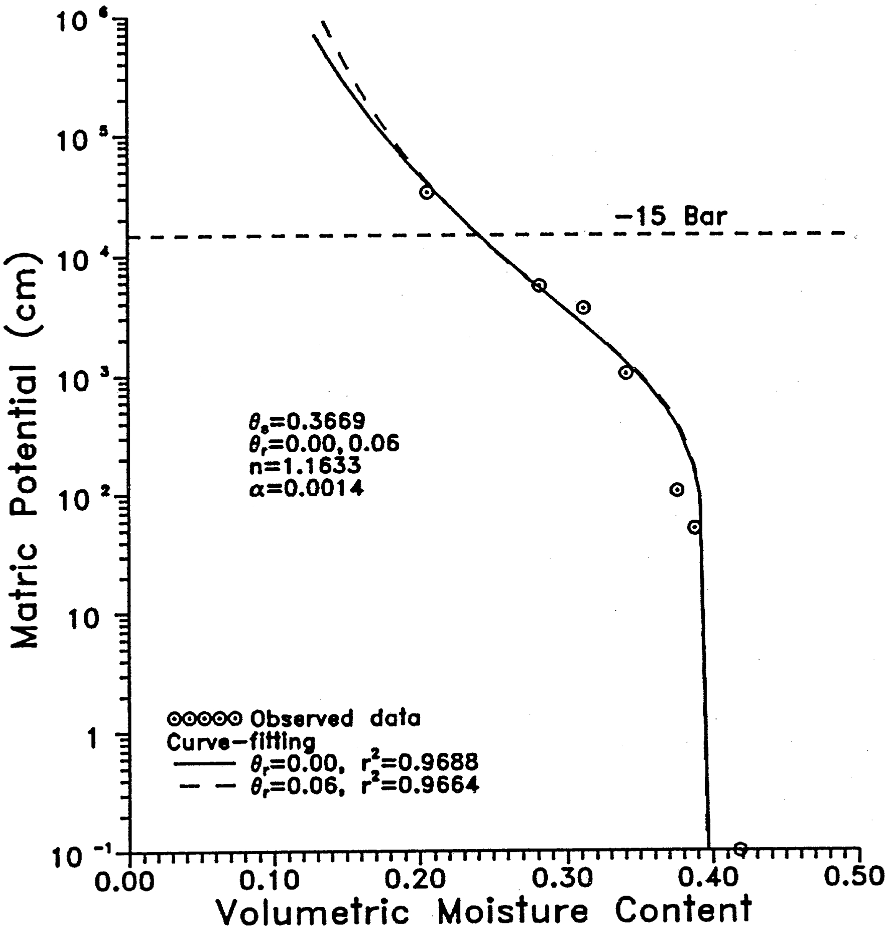

Figure 4. Soil Moisture Characteristics for Burrell CSL Sample 2

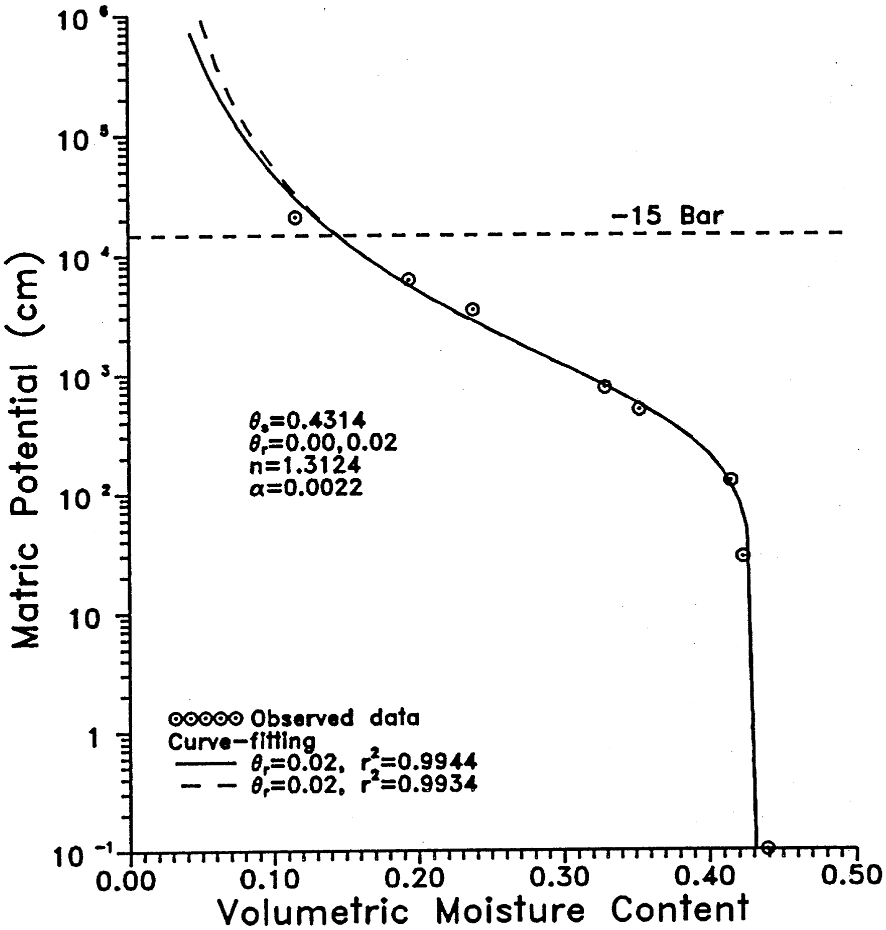

Figure 5. Soil Moisture Characteristics for Hannastown Subsoil Sample 1

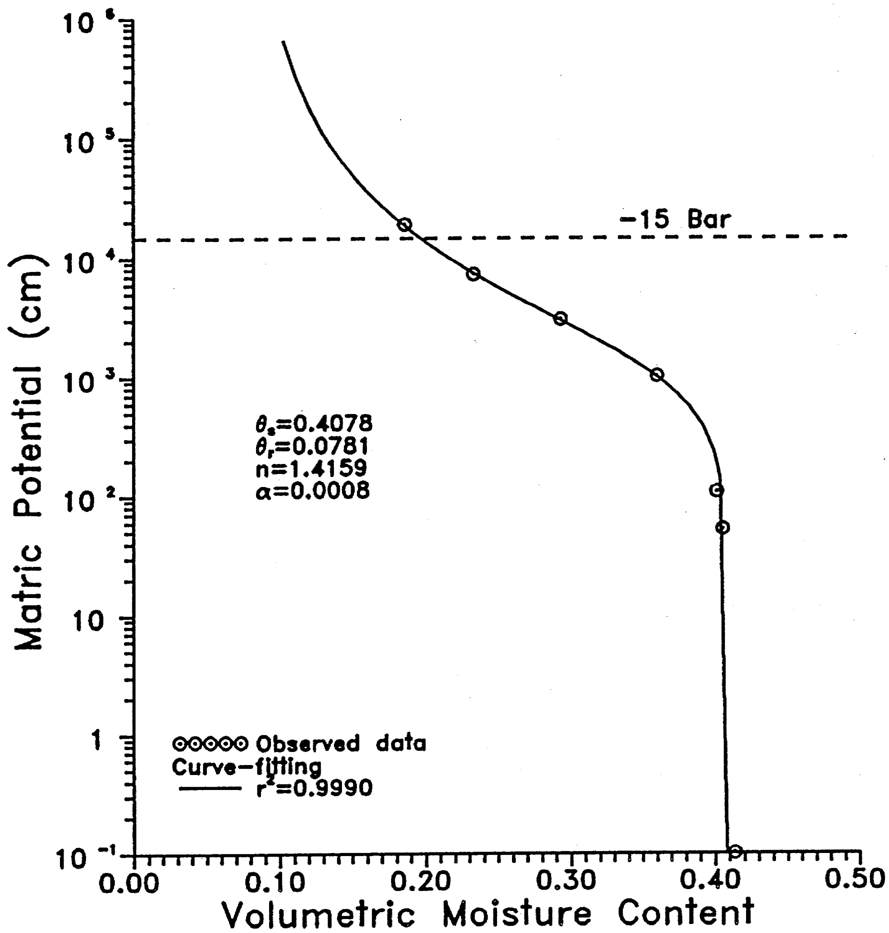

Figure 6. Soil Moisture Characteristics for Hannastown Subsoil Sample 2

4.3 Plant Effects on Radon Release

The UMTRA Project designed the Burrell cover to conform to standards promulgated by EPA for the release rate of ^{222}Rn. The rules in 40 CFR Part 192 require assurance that the release rate not exceed 20 pCi $\cdot$ m^{-2} $\cdot$ s^{-1} "for a period of 1,000 years to the extent reasonably achievable and in any case for at least 200 years when averaged over the disposal area over at least a one-year period." NRC accepts cover design calculations of radon flux attenuation that are calculated with the computer program RADON (NRC 1989) or its predecessor, RAECOM, as a basis for compliance. We used the RADON program to test a range of possible current and future influences of root intrusion and ecological development on radon flux from the cover. Input data for the tests consisted of a combination of the characterization data for the original design (Section 3.0), our field data that depict current conditions at Burrell, and data from the Hannastown analog site that simulate possible future conditions (Section 4.2).

The mathematical model implemented in RADON describes one-dimensional, steady-state radon diffusion through a two-phase multilayer system. The model does not address preferential diffusion in soil macropore structure or active transport through the transpiration stream of plants. Therefore, although RADON is the accepted tool for UMTRA disposal cell covers, it may underestimate increases in flux rates attributable to root intrusion and soil development.

4.3.1 RADON Program Input Data

The RADON program requires input data on radiological and physical properties of tailings and cover layers. Original design values for parameters that should not change appreciably over time or in response to root intrusion were held constant (Table 9).

The test variables presented in the following sections were selected because (1) sensitivity analyses have shown them to be important (e.g., Smith et al. 1985), (2) they are expected to change in the long term, or (3) the field measurements (Section 4.2) show that they are influenced by root intrusion and long-term ecological change.

Table 9. Constants Input to the RADON Program for Calculating Radon Flux From the Burrell Cover

Constant	Description	Source
Tailings Layer Thickness		Table 1
Layer 1	180 cm	
Layer 2	60 cm	
Layer 3	60 cm	
Tailings Dry Bulk Density	1.46 g/cm^3	Completion report (MKE 1994)
Tailings ^{222}Rn Emanation Coefficient	0.15	Table 2
Tailings Water Content	9.0	Completion report (MKE 1994)
Cover ^{222}Rn Emanation Coefficient	0.00	NRC (1989) default value
Cover ^{226}Ra Activity	0.00	NRC (1989) default value

4.3.1.1 ^{226}Ra Activity

The radiological characterization data for Burrell RRM (Section 3.1) underestimate ^{226}Ra activity during the 200- to 1,000-year design life of the cover. Because of initially high ^{230}Th activity in the RRM, values of ^{226}Ra activity will increase over time as a consequence of ^{230}Th decay. Table 10 gives initial (t = 0) ^{226}Ra and ^{230}Th activity as measured during construction of the cell (Table 1) and the serial decay of ^{226}Ra and ^{230}Th through the year t = 1,000. The total ^{226}Ra activity in picocuries per gram at any time t (N_2) was calculated as

$$N_2 = \frac{\lambda_2 (N_1)_0}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t}) + (N_2)_0 e^{-\lambda_2 t} \qquad (1)$$

where

λ_2 = 4.32×10^{-4}, the decay constant for ^{226}Ra,
λ_1 = 8.63×10^{-6}, the decay constant for ^{230}Th,
$(N_1)_0$ = the initial activity of ^{230}Th, and
$(N_2)_0$ = the initial activity of ^{226}Ra.

Table 10. Serial Decay of ^{226}Ra and ^{230}Th at Three Depths Based on Average Activity From As-Built Characterization Data

Time (yr)	Depth (0–60 cm) ^{226}Ra (pCi/g)	Depth (0–60 cm) ^{230}Th (pCi/g)	Depth (60–120 cm) ^{226}Ra (pCi/g)	Depth (60–120 cm) ^{230}Th (pCi/g)	Depth (120–300 cm) ^{226}Ra (pCi/g)	Depth (120–300 cm) ^{230}Th (pCi/g)
0	39.5	416.0	26.2	204.1	79.8	878.5
50	47.5	415.8	30.0	204.0	96.8	878.1
100	55.4	415.6	33.7	203.9	113.5	877.7
150	63.1	415.5	37.3	203.8	129.8	877.3
200	70.6	415.3	40.9	203.7	145.8	876.9
250	78.0	415.1	44.4	203.6	161.4	876.6
300	85.2	414.9	47.8	203.6	176.7	876.2
350	92.2	414.7	51.1	203.5	191.7	875.8
400	99.1	414.6	54.3	203.4	206.3	875.4
450	105.8	414.4	57.5	203.3	220.6	875.1
500	112.4	414.2	60.6	203.2	234.5	874.7
550	118.9	414.0	63.7	203.1	248.2	874.3
600	125.2	413.9	66.7	203.0	261.6	873.9
650	131.3	413.7	69.6	202.9	274.7	873.5
700	137.4	413.5	72.4	202.9	287.5	873.2
750	143.3	413.3	75.2	202.8	300.0	872.8
800	149.0	413.1	77.9	202.7	312.2	872.4
850	154.7	413.0	80.6	202.6	324.2	872.0
900	160.2	412.8	83.2	202.5	335.9	871.7
950	165.6	412.6	85.8	202.4	347.3	871.3
1,000	170.9	412.4	88.2	202.3	358.5	870.9

4.3.1.2 Soil Water Content and Dry-Weight Bulk Density

Soil water content and dry-weight bulk density of the CSL are the two RADON input parameters most influenced by root intrusion and ecological development on the cover. Because radon diffusion of soil is elevated when interconnected pore spaces are filled with air, radon flux is sensitive to the CSL water content and porosity (NRC 1989). RADON calculates porosity as a function of the dry-weight bulk density, assuming a constant specific gravity (2.65 grams per cubic centimeter [g/cm^3]) and the density of water as unity in grams per cubic centimeter.

NRC considers the long-term soil water content of the CSL to be the parameter that introduces the greatest uncertainty in radon attenuation calculations. In the absence of field data, NRC accepts the soil water content at which permanent wilting occurs as a reasonable value of the long-term soil water content. The permanent wilting point used by UMTRA for design calculations is –15 bars (DOE 1989). Water-retention characteristic curves (Figures 3 through 6) indicate that the –15 bar soil water equivalent is about 23 percent by volume for the Burrell CSL and about 15 percent by volume for the Hannastown subsoil. In situ dry-weight bulk densities were 1.76 g/cm^3 for the Burrell CSL and 1.48 g/cm^3 for the Hannastown subsoil (Table 6).

Converting volumetric water content (θ_v) to gravimetric water content (θ_w) as

$$\theta_w = \theta_v(\rho_w / \rho_b) \qquad (2)$$

where ρ_w, the density of water, is taken as unity in grams per cubic centimeter, gives –15 bar gravimetric water content equivalent values for Burrell and Hannastown of 13.1 percent and 10.1 percent, respectively. RADON requires gravimetric values.

The –15 bar soil water equivalent is too conservative an annual average for the humid climate of western Pennsylvania. At the depth of the Burrell CSL, agricultural and woodland soils in western Pennsylvania only rarely dry to –15 bar. NRC also accepts in situ measurements of soil water content if samples are obtained below depths influenced by high seasonal variability. Wet and dry season in situ gravimetric water content in the Burrell CSL for 1995 (Table 7) were not significantly different, and, therefore, provide a reasonable and still conservative annual average value (19.0 percent). The 1995 dry-season water content for the Hannastown subsoil (17.1 percent) is a reasonable long-term value.

4.3.2 RADON Test Matrix

A suite of RADON tests were run encompassing a broad range of current and possible future conditions. Table 11 presents a summary of the factorial test structure.

Table 11. RADON Model Test Structure

Factor	Level		Description
Year	0		Current conditions
	200		Minimum cover design life
	1000		Target cover design life
^{226}Ra Activity ($pCi \cdot m^{-2} \cdot s^{-1}$) in Three Tailings Layers	Layer 1: 0–60 cm	39.5 in year 0 70.6 in year 200 170.9 in year 1,000	^{226}Ra activity derived from serial decay calculations (Table 10) given initial ^{226}Ra and ^{230}Th concentrations sampled in the three tailings layers during construction of the disposal cell (Table 1)
	Layer 2: 60–120 cm	26.2 in year 0 40.9 in year 200 88.2 in year 1,000	
	Layer 3: 120–300 cm	79.8 in year 0 145.8 in year 200 358.5 in year 1,000	
Soil Water Content (gravimetric)	Burrell CSL	13.1%	–15 bar equivalent (Figures 3 and 4)
		19.0%	In situ mean value (Table 7)
	Hannastown	10.1%	–15 bar equivalent (Figures 5 and 6)
		17.1%	In situ mean value (Table 7)
Dry-Weight Bulk Density (g/cm^3)	Burrell CSL	1.76	In situ mean value (Table 6)
	Hannastown	1.48	In situ mean value (Table 6)
CSL Layer Thickness (cm)	0.0		Radon flux calculated given no CSL
	90.0		Actual thickness of the Burrell CSL
	Optimum		RADON calculates the thickness required to maintain ^{222}Rn flux below the 20 $pCi \cdot m^{-2} \cdot s^{-1}$ standard

4.3.3 RADON Test Results and Discussion

Table 12 presents a summary of the RADON model test results. Given the constraints and assumptions of the RADON calculations and input data, ^{222}Rn flux levels at the surface of the Burrell disposal cell should not exceed the standard within 1,000 years if the CSL remains intact and dries no more than measured dry-season field conditions in the Hannastown analog subsoil.

Given current ^{226}Ra levels in the RRM, it appears there is no need for a CSL in the cover (Tests 1 through 5). Flux rates at the surface of the RRM in the year $t = 0$ barely exceed the standard (Test 1). Therefore, a CSL less than 10-cm thick would be more than adequate for compliance with the standard (Tests 2 and 4). The 90-cm CSL maintains flux rates below 1.0 $pCi \cdot m^{-2} \cdot s^{-1}$ regardless of root intrusion because present-day plant growth has no significant effect on CSL water content (Test 3). Even for the unlikely scenario that plant transpiration dries the CSL water content to –15 bar, flux rates remain below 1.0 $pCi \cdot m^{-2} \cdot s^{-1}$ (Test 5).

Table 12. *RADON Model Test Results (shaded results are for analog site conditions)*

Test No.	Time (0 + *t*)	^{226}Ra Activity (pCi/g) in Three RRM Layers[b] 0–60 cm	60–120 cm	120–300 cm	CSL θ_w [c] (wt.%)	CSL ρ_b [d] (g/cm^3)	Test Results[a] CSL (cm)	Test Results[a] Rn Flux (pCi · m^{-2} · s^{-1})
1	0	39.5	26.2	79.8	—	—	0.0	23.6
2	0	39.5	26.2	79.8	19.0	1.76	<10.0	20.0
3	0	39.5	26.2	79.8	19.0	1.76	90.0	< 0.1
4	0	39.5	26.2	79.8	13.1	1.76	<10.0	20.0
5	0	39.5	26.2	79.8	13.1	1.76	90.0	0.8
6	200	70.6	40.9	145.8	—	—	0.0	42.0
7	200	70.6	40.9	145.8	19.0	1.76	<10.0	20.0
8	200	70.6	40.9	145.8	19.0	1.76	90.0	15.7
9	200	70.6	40.9	145.8	13.1	1.76	25.1	20.0
10	200	70.6	40.9	145.8	13.1	1.76	90.0	1.3
11	200	70.6	40.9	145.8	17.1	1.48	26.5	20.0
12	200	70.6	40.9	145.8	17.1	1.48	90.0	6.3
13	200	70.6	40.9	145.8	10.1	1.48	72.3	20.0
14	200	70.6	40.9	145.8	10.1	1.48	90.0	16.8
15	1,000	170.9	88.2	358.5	—	—	0.0	101.0
16	1,000	170.9	88.2	358.5	19.0	1.76	<10.0	20.0
17	1,000	170.9	88.2	358.5	19.0	1.76	90.0	< 0.1
18	1,000	170.9	88.2	358.5	13.1	1.76	74.7	20.0
19	1,000	170.9	88.2	358.5	13.1	1.76	90.0	3.2
20	1,000	170.9	88.2	358.5	17.1	1.48	73.2	20.0
21	1,000	170.9	88.2	358.5	17.1	1.48	90.0	15.2
22	1,000	170.9	88.2	358.5	10.1	1.48	163.3	20.0
23	1,000	170.9	88.2	358.5	10.1	1.48	90.0	40.5

[a]All test results are output of the RADON code (NRC 1989).

[b]^{226}Ra activity (pCi/g) for the years 0, 200, and 1,000 are based on characterization of ^{226}Ra and ^{230}Th activities in the cell during construction (Table 1) and calculation of their serial decay values (Table 9).

[c]θ_w values: 13.1% was derived from the volumetric moisture retention curve for the Burrell CSL at –15 bar matric potential (Figures 3 and 4), 19.0% was the dry-season mean for 1995 (Table 7), 17.1% was the dry-season mean for the Hannastown analog subsoil (Table 7), and 10.1% was derived from the volumetric moisture retention curve for the Hannastown analog subsoil at –15 bar matric potential (Figures 5 and 6).

[d]ρ_b values: 1.76 and 1.48 g/cm^3 are in situ values for the Burrell CSL and the Hannastown analog subsoil, respectively (Table 6).

Tests 6 through 14 results are for ^{226}Ra activity levels in the year $t = 200$. Flux rates at the surface of the RRM (Test 6) are more than twice the standard (42.0 $pCi \cdot m^{-2} \cdot s^{-1}$). However, a CSL less than 10-cm thick would be adequate, given in situ soil water data (Test 7). A minimum 25-cm-thick CSL would be needed, assuming the –15 bar water content (Test 9). Therefore, a 90-cm CSL remains more than adequate to meet the flux standard at the surface of the disposal cell (Tests 8 and 10), even if it degrades and dries to conditions equivalent to the Hannastown subsoil bulk density, porosity, or –15 bar moisture (Tests 11 through 14).

For the 1,000-year ^{226}Ra activity levels (Tests 15 through 23), ^{222}Rn flux rates at the top of the RRM exceed 100 $pCi \cdot m^{-2} \cdot s^{-1}$ (Test 15). Given the unlikely assumption that in situ bulk density and porosity at Burrell will remain unchanged, a CSL less than 10 cm thick would be adequate if soil water also remains unchanged (Test 16); a minimum 75-cm CSL would be needed if soil water content dropped to the –15 bar equivalent (Test 18). Therefore, for Burrell conditions, the 90-cm CSL remains adequate (Tests 17 and 19).

A 90-cm CSL on the disposal cell with dry-season field conditions equivalent to the Hannastown analog subsoil is also adequate to meet the standard (Test 21). However, if unforeseen ecological development and changes in climatic conditions would cause the CSL to dry to –15 bar (Test 23), annual average surface flux rates averaged over the surface of a 90-cm CSL may double the standard (40.5 $pCi \cdot m^{-2} \cdot s^{-1}$). For this unlikely scenario, a minimum CSL thickness of 163 cm is needed (Test 22).

In summary, the Hannastown soil is (on a thickness basis) a less effective radon barrier than the present Burrell soil. If changes in the Burrell soil cause it to become more like the Hannastown soil, and it then dries to –15 bar, the radon flux could exceed the standard.

4.4 Plant Effects on Water Infiltration

The UMTRA Ground Water Project is in the process of evaluating and developing remedial action strategies to ensure that amounts of RRM and associated hazardous constituents in the ground water at inactive millsites comply with the criteria of 60 FR 2854 (Section 2.2.2). This activity is moving forward under the assumption that the source of ground-water contamination has been contained. If disposal cells fail to control contaminant seepage, a source for continued ground-water contamination, then ongoing assessments and remedial action to treat contaminant plumes may have little long-term value.

Engineered covers on disposal cells are designed to limit the amount of water that passes into underlying RRM, potentially mobilizing and moving contaminants into aquifers. Passage of water can be controlled by lateral drainage layers, by CSLs, and by evapotranspiration. Plant growth and root intrusion can greatly influence all three processes (Section 2.3). At humid sites like Burrell where CSLs have been constructed as the primary barrier to water infiltration, macropore structure in the CSL created by root intrusion and soil development is of greatest concern (Meyer et al. 1996). Root channels and eventually earthworms, burrowing animals, soil structural changes, and other heterogeneities can combine to promote preferred pathways for flow of water.

At Burrell, given high precipitation and a CSL that is often saturated (Section 4.2), the passage of water through the cover is sensitive to changes in the saturated hydraulic conductivity. Under these conditions, the hydraulic gradient is approximately 1 and water flux through the CSL (Q^{CSL}) can be calculated with Darcy's law (Meyer et al. 1996) as

$$Q^{CSL} = K_{sat} \cdot I \tag{3}$$

where

K_{sat} = vertical saturated conductivity of the CSL,
I = vertical gradient across the CSL, calculated as $(H + T)/T$,
H = head of water above the CSL, and
T = thickness of the CSL.

Under saturated conditions, when H is small with respect to T, water flux through the CSL is approximated by K_{sat}. Therefore, the objective of this phase of the study was to obtain in situ measurements of the effects of root intrusion and soil development on K_{sat}.

4.4.1 In Situ Measurement of Saturated Hydraulic Conductivity

Air-entry permeameters (AEPs) (ASTM D5126) were used to estimate in situ changes in saturated hydraulic conductivity and preferential flow attributable to root intrusion and soil development. The AEPs were designed and manufactured by Daniel B. Stephens and Associates, Inc., for use on engineered clay layers and other low-permeability clay soils (Stephens et al. 1988; Havlena and Stephens 1992). Each AEP, based on a design by Bouwer (1966), consists of a round, 30-cm-deep permeameter ring, air-tight cover, standpipe, graduated water reservoir, and vacuum gauge.

The AEP tests were designed to capture a reasonable range of current and possible future conditions on the cover. Replicate AEP tests were conducted on the cover in areas without plants (n = 3), on the cover where woody plants have rooted into the CSL (n = 6), and at the Hannastown analog site (n = 3). Permeameter rings were driven into the cover CSL or analog subsoil after removing overlying materials (rock and bedding layers on the cover and plow-layer soil at Hannastown). The CSL-with-plants tests included three Japanese knotweed plants and three dominant tree species (sycamore, black locust, and staghorn sumac). Foliage density and leaf area index of these plants were determined before they were cut (see Section 4.4.2). After installing a permeameter ring, we sealed polycarbonate plates to the ring top, attached standpipes and water reservoirs, and filled the reservoirs. Reservoir water was dyed to trace wetting fronts and preferred flow paths. The two-stage test consisted of (1) measuring the rate of water-level drop in the reservoir and (2) measuring the pressure (tension) with the vacuum gauge after shutting off the water supply and allowing water to redistribute. The vacuum gauge measurement was used to calculate the air-entry or bubbling pressure of the soil (ASTM D5126).

Three different methods corresponding to three different conditions encountered during the tests were used to calculate K_{sat} :

(1) The Bouwer (1966) method, which assumes initially unsaturated soil, was used for the analog soils.

(2) The Young et al. (1995) method, which assumes initially saturated or nearly saturated soil and deep seepage, was used for most of the cover tests with plants.

(3) The Young et al. (1995) method, which assumes initially saturated or nearly saturated soil and ***no*** deep seepage, was used for cover tests without plants and one test with plants where water moved to the surface after a period of monitoring.

Saturated conductivity (K_{sat} in centimeters per second) for condition (1) was calculated as

$$K_{sat} = [2 \cdot dH/dT \cdot L \cdot (R_{ws}/R_{sr})2]/[H_f + L - (0.5 \cdot P_a)] \qquad (4)$$

where

dH = change in head,
dT = change in time,
L = depth of soil surface to wetting front,
R_{ws} = radius of water supply reservoir,
R_{sr} = radius of AEP soil ring,
H_f = last head reading,
P_a = $P_{min} + G + L$,
P_{min} = gauge pressure at air entry (negative value), and
G = height of gauge above the soil surface.

K_{sat} for conditions (2) and (3) was determined using Equation (5) (Young et al. 1995):

$$[K_{sat} \cdot \mathrm{R_{sr}} \cdot (t_2 - t_1)]/(\pi r^2 \cdot N) = \ln(S_1 \cdot H_1) - \ln(S_2 \cdot \mathrm{H_2}) \qquad (5)$$

where H_1 and H_2 are the heads at times t_1 and t_2, respectively; S_1 and S_2 are shape factors presented in Table 1 of Young et al. (1995) for flow into saturated soil, r is the radius of the standpipe, and N, a shape factor dependent on the depth of penetration of the permeameter ring, d, is calculated as

$$N = 0.316 \cdot (d/a) + 0.184. \qquad (6)$$

4.4.2 Plant Canopy Measurements

Measurements of the plant canopy structure were used to compare attributes of plant communities indicative of the functional performance of the Burrell cover and the Hannastown analog site. Canopy structure plays a fundamental role in physiological processes such as evapotranspiration (McNaughton and Jarvis 1983), biomass productivity (deWit 1965), and radiation interception (Ross 1981). The structure or architecture of individual plant canopies can also be used as a weighting factor to project, over the greater community, other attributes of individual plants, such as rooting influences on soil water (Pearcy et al. 1989).

We evaluated the canopy structure of individual Japanese knotweed plants that were selected for in situ K_{sat} tests. Measurements of leaf area index (LAI, leaf area per unit ground area) and foliage density (foliage area per unit canopy volume) of plants used for K_{sat} tests were made before excavation of plants and installation of permeameter rings. The canopy volume of each plant was estimated from a sufficient number of x,y coordinate dimensions to describe the shape of the canopy. The foliage density of these plants was measured with an LAI–2000 Plant Canopy Analyzer (LI–COR, Inc. 1992). The LAI–2000 provides an indirect but accurate estimate of foliage density and LAI using "fish-eye" lens measurements of canopy gap fractions (the fraction of the sky visible through the canopy) at various angles (Welles and Norman 1991). A view restrictor was placed over the lens to limit the sensor's azimuthal field of view to 90°, and readings were taken with the LAI–2000 in four quadrants at the base of each plant. Using 2000–90 software from LI-COR, Inc. (1992), we calculated LAI within the drip line, or drip-line LAI (DLLAI), as

$$\text{DLLAI} = \text{Foliage Area Density} \cdot (\text{Canopy Volume/Drip-Line Area}). \qquad (7)$$

We also used the LAI–2000 to measure plant-community LAI on the Burrell cover and at the Hannastown analog site. One hundred pre-dawn readings were taken at random locations within the patchy Japanese knotweed-dominated stand on the Burrell cover. At Hannastown, two stands were measured: (1) a relatively open, mixed deciduous canopy with abundant understory growth (Hannastown 1) and (2) the closed-canopy sugar maple stand where we measured in situ K_{sat} (Hannastown 2). In both stands, 25 random readings provided satisfactory statistics. Hannastown 1 was a pasture when the soil survey photographs were taken in 1967; the woodland, therefore, is less than 30 years old. The sugar maple stand at Hannastown 2 may be more than 100 years old, the oldest sere on Westmoreland soil in the park.

4.4.3 In Situ Saturated Hydraulic Conductivity Results and Discussion

Table 13 presents the in situ saturated hydraulic conductivity (K_{sat}) test results; Table 14 presents plant canopy structure results for the K_{sat} test plants. Results for four conditions are presented: (1) the Burrell CSL without plants, (2) the Burrell CSL with Japanese knotweed, (3) the Burrell CSL with trees and (4) the Hannastown analog subsoil. For all Burrell cover tests, field soil-water content values were at saturation (Tables 7 and 8), and water was observed ponding in AEP test pits. Therefore, for the purposes of this study, water flux through the CSL (Q^{CSL}) can be approximated by K_{sat}.

Table 13. Air-Entry Permeameter Tests of In Situ Saturated Hydraulic Conductivity (K_{sat}) *in the Burrell CSL and the Hannastown Analog Subsoil*

Conditions Tested	K_{sat} (cm/s)	K_{sat} (mean) [a]	Calculation Method
Burrell CSL/No Plants			
Replicate 1	1.8×10^{-7}	2.9×10^{-7}(a)	Equation (5)[b]
Replicate 2	6.0×10^{-7}		Equation (5)[b]
Replicate 3	1.0×10^{-7}		Equation (5)[b]
Burrell CSL/ Japanese Knotweed			
Replicate 1	1.6×10^{-6}	3.0×10^{-5}(b)	Equation (5)
Replicate 2	5.8×10^{-5}		Equation (5)
Replicate 3	6.1×10^{-4} [c]		Equation (5)[b]
Burrell CSL/Trees			
Sycamore	4.0×10^{-7}	4.8×10^{-7}(a)	Equation (5)
Staghorn sumac	7.4×10^{-7}		Equation (5)
Black locust	3.1×10^{-7}		Equation (5)
Hannastown Analog Subsoil			
Replicate 1	1.2×10^{-4}	1.3×10^{-4}(c)	Equation (4)
Replicate 2	1.2×10^{-4}		Equation (4)
Replicate 3	1.2×10^{-4}		Equation (4)

[a]Mean values followed by the same letter were not significantly different at $\alpha = 0.05$.
[b]Shape factors used for calculation were based on the assumption of no deep seepage.
[c]This value was excluded from the mean because water may have seeped along the permeameter wall, resulting in an inflated K_{sat} value.

Table 14. Canopy Dimensions, Foliage Density, and Drip-Line LAI for Plants on the Burrell Cover Used for K_{sat} *Tests*

Plant	Height (m)	Mean Diameter (m)	Foliage Density[a]	Mean[b]	Canopy Vol. (m^3)	Drip-Line Area (m^2)	DLLAI[c]	Mean
Japanese knotweed								
Replicate 1	1.85	2.81	4.2	4.2(a)	6.7	5.3	5.4	4.7(a)
Replicate 2	2.4	4.25	3.7		15.2	16.9	3.3	
Replicate 3	1.8	3.68	4.7		8.1	7.1	5.4	
Trees								
Sycamore	3.39	1.72	2.6	2.3(b)	3.3	2.3	3.7	3.4(a)
Staghorn sumac	2.71	2.92	1.9		13.6	9.6	2.7	
Black locust	3.87	2.34	2.3		28.5	17.2	3.8	

[a]Foliage area per unit canopy volume.
[b]Mean values followed by the same letter were not significantly different at $\alpha = 0.05$.
[c]Drip-line leaf area index.

4.4.3.1 Burrell CSL Without Plants

At locations on the disposal cell where plants have ***not*** rooted, the in situ K_{sat} of 2.9 x 10^{-7} cm/s (Table 13), or a Q^{CSL} of 0.25 millimeter per day (mm/d), was about 3 times greater than the design standard for a CSL (1 x 10^{-7} cm/s) required by both UMTRA (DOE 1989) and RCRA subtitle C (EPA 1989). In situ measurements were as much as an order of magnitude greater than laboratory falling-head results for the same soil (2.6 x 10^{-8} cm/s, Table 8). This discrepancy appears to agree with Rogowsky (1990), who conducted field-scale tests in Pennsylvania comparing the aerial variation in hydraulic conductivity of an engineered compacted clay, similar to the Burrell CSL, with laboratory values. Unlike the fairly homogenous recompacted clay used in laboratory column tests, water and solutes may move in the CSL through only a small portion of the total porosity. Elsbury et al. (1990) suggest that the persistence of clods and the failure of soil lifts to bond can lead to macropore flow between clods and lifts.

Table 15. LAIs on the Burrell Cover and at the Hannastown Site

Site	Date	Start Time	Finish Time	LAI[a] Mean	LAI[a] SE (mean)[b]	Visible Sky (%)[c]	n[d]
Burrell Cover	July 28, 1995	19:47	20:45	0.65	0.07	57.9	100
Hannastown 1	July 27, 1995	19:38	19:56	4.86	0.19	1.4	25
Hannastown 2	July 27, 1995	18:59	19:37	5.37	0.04	1.0	25

[a]LAI is a dimensionless measure of "How much foliage?" LAI can be thought of as m^2 foliage area/m^2 ground area.
[b]Standard error of the mean.
[c]"Visible sky" is an indicator of canopy light absorption.
[d]The number of sample points (n) were located using random points along transects originating at random locations along a baseline.

4.4.3.2 Burrell CSL With Plants

Root intrusion effects on K_{sat} were tested for four species: Japanese knotweed and sycamore, staghorn sumac, and black locust trees. Japanese knotweed roots increased the Burrell CSL K_{sat} by two orders of magnitude (3.0 x 10^{-5} cm/s, Table 8); a daily Q^{CSL} of 26.0 mm. Japanese knotweed taproots grew vertically through the drainage layer of sand and gravel, then diverted laterally at the surface of the CSL. Many secondary and fibrous roots branched vertically into the CSL. The height of Japanese knotweed test plants varied little (mean = 2.0 m); however, canopy volume and drip-line area were highly variable (Table 14). In contrast, the CSL K_{sat} in the rooting zone of the three tree species (4.8 x 10^{-7} cm/s; Q^{CSL} = 0.41 mm/d) and the CSL K_{sat} with no plants were not significantly different (Table 13). The test trees were taller than Japanese knotweed but had significantly lower foliage density (Table 14). Tree roots clogged the drainage layer, but only a small percentage of their root biomass was observed in the CSL.

LAI of individual Japanese knotweed test plants on the Burrell cover (Table 14) and the plant-community LAI for the Burrell cover (Table 15) were used to estimated a weighted-average K_{sat} for the entire disposal cell cover (4.4 x 10^{-6} cm/s; Q^{CSL} = 3.8 mm/d). The calculation was based on the following assumptions: (1) the LAI of the Burrell plant community is dominated by Japanese knotweed, (2) the test plants were representative of the stand, and (3) test-plant K_{sat}

measurements were representative of conditions within the drip line. Given these caveats, we conclude that root intrusion may already have increased the Burrell CSL K_{sat} more than tenfold.

4.4.3.3 Hannastown Analog Site K_{sat}

Measurements of K_{sat} and LAI at the Hannastown analog site are considered a reasonable upper range for future conditions on the Burrell cover. A comparison of the Burrell CSL and Hannastown subsoil shows that

- The Burrell CSL consists of recompacted Westmoreland series soil (27 percent clay); the Hannastown subsoil is also Westmoreland series (29 percent clay).

- The Burrell CSL underlies a gravely sand drainage layer. Where mature plants were uprooted for AEP tests, the upper 10 to 15 cm of the drainage layer was filled with organic matter derived from plant litter. The Hannastown subsoil underlies a silt loam plow layer high in organic matter. The drainage layer may become more like the plow layer with time.

- The Burrell CSL bulk density (1.76 g/cm) was much higher than the Hannastown subsoil bulk density (1.48 g/cm). It could be argued that the lower Hannastown bulk density, higher porosity, and higher K_{sat} will not occur in the engineered Burrell CSL and, therefore, Hannastown is a poor analog. Conversely, the Hannastown subsoil is residuum derived from interbedded calcareous shale, sandstone, and limestone and, therefore, originally had a much higher bulk density than the Burrell CSL. We can expect the porosity of the engineered CSL to increase in response to soil development processes. The Hannastown soil is a reasonable analog of the long-term condition.

- Hannastown has a higher laboratory K_{sat} and saturated water content as expected, given the higher porosity.

The Hannastown subsoil was literally teeming with life (e.g., roots, earthworms, insects) all contributing to preferred pathways for flow of water. The Hannastown K_{sat} (1.3×10^{-4}) was nearly 3 orders of magnitude higher than the Burrell CSL K_{sat} without plants. Dye was used to trace water movement patterns during AEP tests (Section 4.4.1). Excavation of soil profiles following AEP measurements revealed dye on coarse and fine root surfaces, in earthworm holes, and along planes of weakness between soil peds.

In situ measurements of hydraulic conductivity in analog soils, like the Hannastown subsoil, may provide the most defensible predictions of future effects of ecological succession and soil development on the performance of CSLs, particularly in humid regions. In contrast, methods for characterizing sizes, configurations, and distributions of macropores in humid soils has only recently been evaluated; no reliable methods exist for numerically predicting water infiltration and recharge rates through these preferred pathways (Meyer et al. 1996).

4.4.3.4 Changes in Plant Canopy Structure

The LAI chronosequence for Burrell and Hannastown plant communities (Table 15) provides clues for possible future changes in the plant canopy structure on the engineered cover. Hannastown 1 is a 30-year-old mixed deciduous open woodland sere in an abandoned pasture. Hannastown 2, the second-growth closed-canopy sugar maple woodland, is perhaps more than 100 years old. A comparison of stands suggests that the Burrell LAI, presently 0.65, may increase sevenfold within 30 years as the community begins to resemble Hannastown 1. This increase in LAI will most likely result in higher evapotranspiration rates and, on average, a drier CSL. The lower standard deviation for LAI at Hannastown 1 than at Hannastown 2 reflects increased uniformity in the canopy over time.

5.0 Phase IV: Implementation

Plant succession and soil development are inevitable on the Burrell disposal cell. Within a few years after construction, a plant community dominated by Japanese knotweed established on the cover, several species rooted in the CSL, and an organic soil began to develop in the drainage layer. Current UMTRA guidance advocates chemical control of plant growth for the design life of the disposal cell (200 to 1,000 years). The LTSM Program evaluated current and possible long-term consequences of root intrusion and ecological change on cover design standards as a basis for a reasonable vegetation management strategy. The study emphasized field measurements of plant effects on radon attenuation and water infiltration in the CSL and in a natural (analog) system that represents a reasonable condition of the cover following unabated ecological and soil development.

5.1 Conclusions

Calculations of radon flux for a suite of possible current and future scenarios suggest that the 90-cm CSL is adequate to hold radon releases below the 20 $pCi \cdot m^{-2} \cdot s^{-1}$ design standard. The RADON model, developed and recommended by NRC, was used to calculate radon flux rates. Root growth presently has no significant influence on soil water content in the nearly saturated CSL nor, according to RADON calculations, on radon diffusion. As ^{230}Th decay raises ^{226}Ra activity levels over time, ^{222}Rn flux rates will increase. In 200 years, the CSL will still be adequate even as it degrades. For the 1,000-year scenario that uses current dry-season values of soil water content as measured at the analog site, calculations with the RADON model suggest that the CSL will continue to perform adequately; flux rates exceed the standard only for the unlikely scenario that the CSL degrades and the average moisture content drops to a level equivalent to –15 bar in the analog soil.

At Burrell, the most detrimental effect of root intrusion and ecological change, now and in the future, is the development of soil macropores in the CSL, which is the primary barrier to water infiltration. Water flux through the CSL can be approximated by the saturated hydraulic conductivity (K_{sat}) given the saturated and nearly saturated conditions. In situ measurements of K_{sat} within the root zone of Japanese knotweed show that the potential for water flux through the CSL is already 2 orders of magnitude above the design standard. Normalized for LAI, the K_{sat} value is an average of more than 10 times the standard over the entire disposal cell. Measurements at the analog site indicate that the plant canopy will increase sevenfold within 30 years and the K_{sat} value will continue to increase as root channels, earthworm holes, and structural planes create preferred flow paths through the CSL. In 200 to 1,000 years, the K_{sat} value may exceed the design standard by more than 3 orders of magnitude (1.3×10^{-4} cm/s). Although the greater plant canopy will raise evapotranspiration rates and may reduce the frequency of saturated flow events, higher K_{sat} values would most likely lead to significant recharge through underlying RRM. Periodic control of plant growth on the cover may slow down soil development, changes in soil hydraulic properties, and consequent increases in water infiltration. However, physical soil development processes, such as freeze-thaw cycles, secondary mineralization, and aggregation of fines, will continue.

5.2 Recommendations

The results of this study indicate that the plant community presently growing on the Burrell disposal cell is significantly increasing water flow into buried RRM. Water movement through the cover may presently be as much as 10 times the design standard and could increase to more than 1,000 times the standard during the design life of the cell. A two-stage course of action is recommended:

1. Implement an interim herbicide spray program to control plant growth and root intrusion of the CSL. The program should target Japanese knotweed because this plant has had the greatest effect on the performance of the cover. Past herbicide applications at Burrell have failed to control Japanese knotweed.

2. Conduct a screening-level risk assessment to evaluate the potential risks to human health and the environment associated with water infiltration of the cover and recharge through buried waste. The risk assessment methodology used by the UMTRA Ground Water Program should be implemented (DOE 1995a).

If the risk assessment indicates that increases in water infiltration at Burrell equivalent to that measured by this study do not pose a significant risk to human health and the environment, maintenance of the cell need consist only of cutting mature trees to prevent pitting of the CSL as a consequence of tree fall (Section 2.3.3). If the assessment indicates that the increased water infiltration does pose a significant risk, corrective action to modify the cover design may be warranted.

6.0 References

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